Stellarator Magnets using High Temperature Superconductors and Advanced Manufacturing

Fusion Review Meeting
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PI: David Anderson, Type One Energy Group
Co-PI's: Robert Granetz, MIT
Brandon Sorbon, CFS
Lianyi Chen, UW-Madison

CHANGING WHAT'S POSSIBLE

Team members and roles

Prof. David Anderson – Principal Investigator (technical direction)

Paul Harris – CTO (cable fab, freeform bending, assembly)

Randall Volberg – CEO (proj. mgmt, AM development., grant admin)

Robert Granetz – co-PI (cable design, fabrication, testing)

Amanda Hubbard – Research Scientist (soldering)

Nicolo Riva – Postdoctoral Associate (cable simulations)

Rui Vieira – Head Engineering (fabrication)

Dave Arsenault – Technician (fabrication)

Brandon Sorbom – CSO (co-PI)

Alex Warner – Lead Manufacturing Engineer

Joy Dunn – Head of Operations

Rich Holcomb – Head of Construction & Facilities

Sean Parnett – Environmental Health & Safety

Nick Jeffers - Head Of Manufacturing

Vincent Fry – Mechanical Engineering

Jeremy Hollman – Head of R&D

David Chavarria – Lead Manufacturing Equipment Engineer

Asst Prof Lianyi Chen – co-PI (AM metallurgy, DFAM)

High-level motivation, innovation, and goals of the project

- Stellarators second only to tokamaks in triple product achieved
- Positive attributes for reactors:
  - Stable, inherent steady state
  - Low recirculating power
  - Capable of high density operation
- High <u>**B**</u> operation is a gamechanger
- (Nearly) perfect application of HTS:
  - Improved confinement
  - Smaller size
- Challenges:
  - 3D structure of the coils
  - Large forces at high fields

Goals

- Find a way to use HTS tapes in a stellarator coil of interest
- Find a way to form tapes/cable into the needed 3D shape with needed accuracy
- Find a way to support the tapes/cable against the magnetic loads.

Approach

- Build upon the groundbreaking work at MIT developing the 'VIPER' cable
- Advance bending methods to needed accuracy to shape the coils
- Utilize advanced manufacturing (3D printing) to build support structure

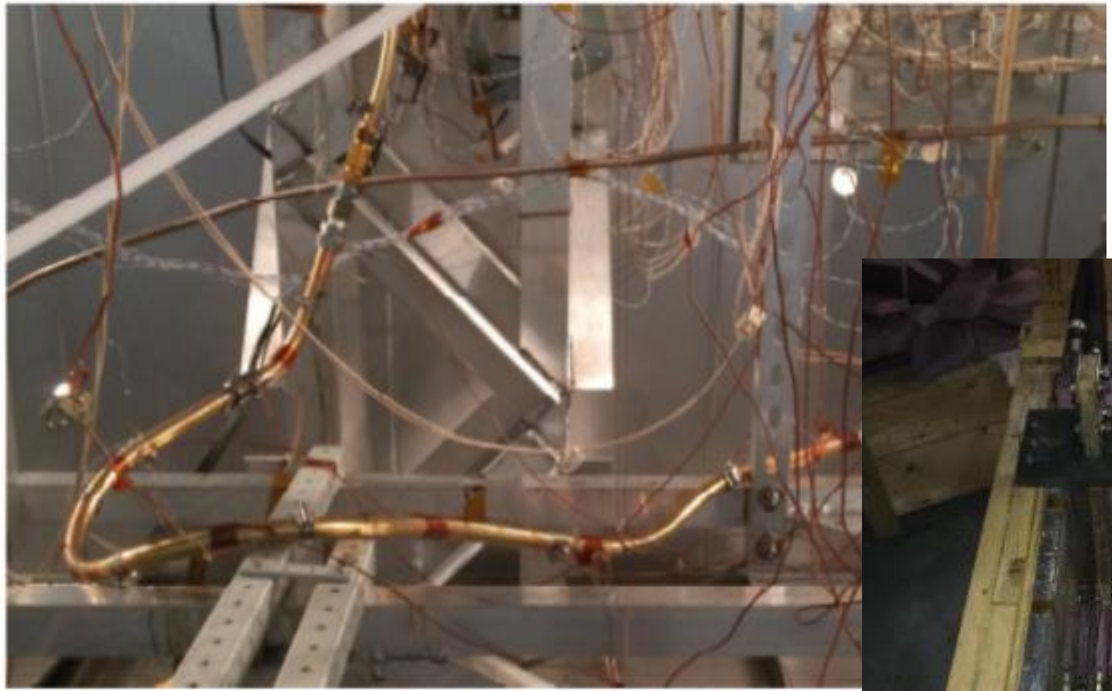
Major tasks, milestones, risks, and desired project outcomes

- Cable bender at CFS operational
  - Date: 8/18/22
  - Risk: Shipping delay or damage
- MS 2.1 Bend dummy coils with no HTS tapes; refine program
  - Date: 10/9/22
  - Risk: Many trials to get needed accuracy or too much variance
- MS 2.3 Bend the final article with HTS tapes included.
  - Date: 10/27/22
  - Risk: Not ready to execute
- MS 2.3b Solder and test the final coil
  - Date: 12/5/22
  - Risk: Time collisions on CFS/MIT resources
- MS 2.5 Assemble cable and support plates
  - Date: 12/15/22
  - Risk: Issues not foreseen after MS 2.3 checks
- MS 2.6 Project Closure 1/12/23

Project outcome: Demonstration of a methodology to fabricate 3D stellarator HTS coils

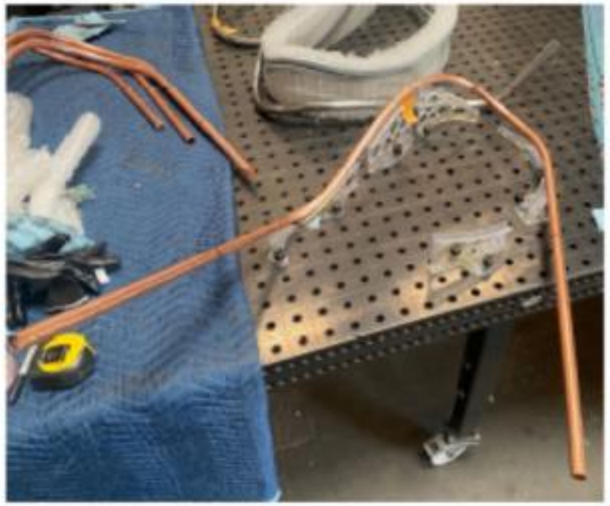
Fabrication of HTS test coil

HTS tape stacks are wound into channels in copper core and inserted into copper jacket



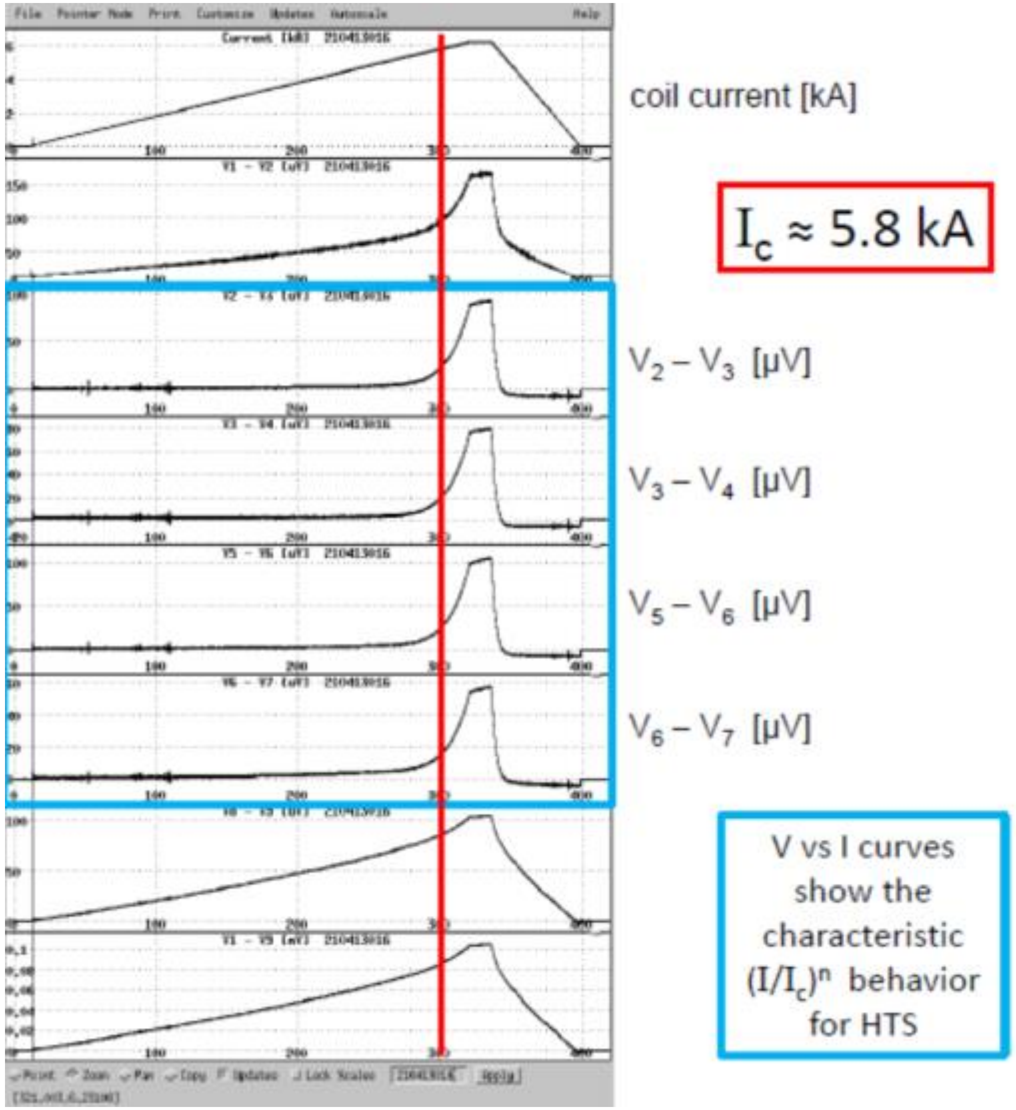
VPI soldering of bent cable

Critical current testing



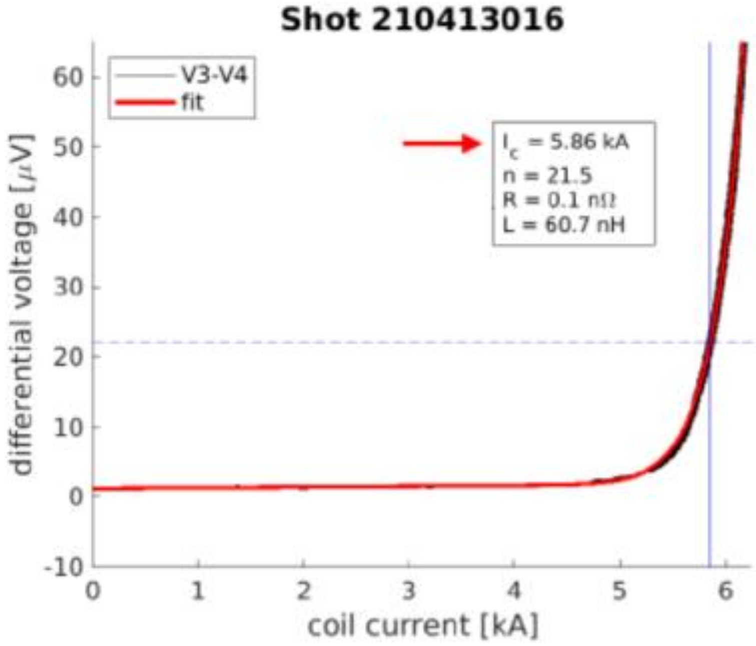
Cable is shaped to non-planar geometry within required tolerance

No reduction of the critical current or characteristic exponent after tape stacking, cabling, bending into shape with multiple tight radius bends and soldering!



MILESTONE 1.8

Test data



Results match a model calculation based on measured I_{crit} and n for individual virgin HTS tapes right off the supply reel.

Fitted function:

$$V(I) = V_0 \left(\frac{I}{I_c}\right)^n + RI + L\frac{dI}{dt}$$

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Extensive simulations of tapes in cables and coils underway

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CHANGING WHAT'S POSSIBLE

Remaining challenges

Non-Planar Shaping of HTS Coil

- We have successfully shaped VIPER cables to non-planar magnet centroid
- +/-1 mm tolerance targets hit on trials
- In current phase, shaping full coil for final magnet

rending of 7/8-turn
non-planar cable

Coil conductor support plates

- Exploring multi hybrid AM processes to:
  - scale to reactor-sized component builds
  - net shape with no post processing handoffs (in-situ coldwork, finishing, etc.)
  - selective high tolerance where needed
  - excellent material properties (no cracks, porosity, residual stress, etc.)
- Satisfied all Phase 1 milestones & now working on final magnet radial plates

T2M and aspirational follow-on plans

- HTS magnet development enables more compact power plant through high magnetic field
  - Smaller size = better economics
  - Higher field allows conservatism on plasma physics, less margin required
- AM enables rapid manufacturing of complex, high-tolerance components
  - Potential for 70% reduction in component mass and cost

- Follow-on plans
  - Full-scale HTS prototype coil
  - Optimization of mfg for speed/cost and for multiple components
  - Integrated optimization of coils: physics, engineering, mfg
  - Integrated mfg. platform to build modular stellarator components